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ABSTRACT

The Harappan Culture, one of the oldest known urban civilizations, thrived on the northwest edge of the Thar Desert (India and Pakistan) between 3200 and 1900 BCE. Its demise has been linked to rapid weakening of the summer monsoon at this time, yet reorganization of rivers may also have played a role. We sampled subsurface channel sand bodies predating ca. 4.0 ka and used U-Pb dating of zircon sand grains to constrain their provenance through comparison with the established character of modern river sands. Samples from close to archaeological sites to the north of the desert show little affinity with the Ghaggar-Hakra, the presumed source of the channels. Instead, we see at least two groups of sediments, showing similarities both to the Beas River in the west and to the Yamuna and Sutlej Rivers in the east. The channels were active until after 4.5 ka and were covered by dunes before 1.4 ka, although loss of the Yamuna from the Indus likely occurred as early as 49 ka and no later than 10 ka. Capture of the Yamuna to the east and the Sutlej to the north rerouted water away from the area of the Harappan centers, but this change significantly predated their final collapse.

INTRODUCTION

The major rivers of the world are recognized as powerful geological agents controlling the filling of sedimentary basins and even affecting the structure of mountain belts, yet on shorter timescales, they are also crucial to the human societies that settle on their banks and in their floodplains. Development of early human cultures was influenced by numerous and complicated factors, yet there is increasing recognition that changing environmental conditions may have been a crucial element in allowing societies to flourish or disperse during the Neolithic–mid Holocene (DeMenocal, 2001; Weiss and Bradley, 2001; Wu and Liu, 2004). The Indus Valley, or Harappan, Culture reached its zenith in southwest Asia at 2600–1900 BCE (Possehl, 2002; Kenoyer, 2008). Decline and dispersal after that time has been linked to weakening of the summer monsoon and the consequent onset of rapid aridification (Staubwasser et al., 2003; Wright et al., 2008), which Harappan agriculture may have been unable to adjust to.

While plausible, this model has been questioned because the climatic drying at 4.2 ka seems to precede the Harappan collapse at 3.9 ka (Possehl, 1999), and in their synthesis Madella and Fuller (2006) concluded that no climatic event could be blamed for a sudden end to the urban Harappan. Indeed, even the very existence of a collapse has been called into question (Enzel et al., 1999; Fuller and Madella, 2001). An alternative scenario has been proposed in which the Harappans abandoned their settlements to the northwest of the Thar Desert as a result of the loss of river flow (Misra, 1984; Mughal, 1997; Wright et al., 2008), triggered partly by the drying climate and partly by capture of headwaters away from the Ghaggar-Hakra River at that time (Fig. 1). The devastation caused by flooding of the Indus in 2010 shows how even modern society is vulnerable to changes in river systems. Furthermore, a larger Ghaggar-Hakra River has long been associated with the Hindu legend of a Sarasvati River flowing subparallel with the Indus. In this study, we investigated the evidence for abandoned river channels in the area north of the Thar Desert known as Cholistan (Fig. 1), and provide the first evidence that the Yamuna previously flowed west. Through use of U-Pb zircon dating we reconstruct how the rivers of the western Himalaya have evolved since the late Pleistocene, exploring the links with the archaeology of Harappan urbanism and de-urbanization.

EVIDENCE OF DRAINAGE CAPTURE

Since the early twentieth century, it has been recognized that archaeological sites cluster around the former valley of the Ghaggar-Hakra in western India and Pakistani Punjab in Cholistan (Stein, 1942). Studies of

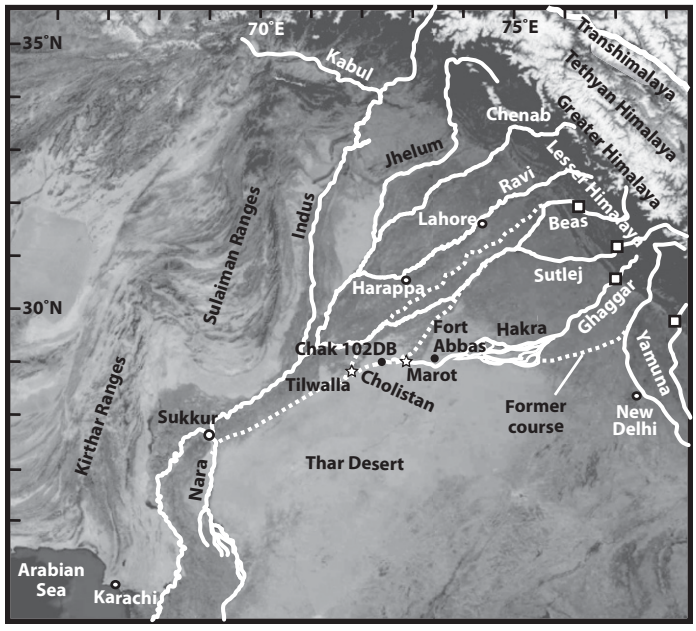

Figure 1. Satellite image of the Indus River system showing the study sites. Stars indicate drilling locations. Black dots indicate trenches. White squares show sampling points on modern river from Alizai et al. (2011a). Buried channels to the east of the study area are from Saini et al. (2009). Dashed lines show former course proposed in this study.

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satellite images have established that a series of desiccated channels exist in the region around this modern ephemeral river (Kar and Ghose, 1984), but little information exists as to when these channels were active. Drilling in India has identified a number of channels dated as having flowed as recently as ca. 6.0–2.9 ka (Saini et al., 2009), yet their relationship to the Harappan sites and to other Himalayan rivers remains obscure. We sampled channel and overbank sediments close to the Harappan sites in Cholistan by drilling to ~45 m depth at two sites and trenching (<5 m) shallower sediments under the modern dune sands (Figs. 1 and 2). Organic carbon was collected and dated using accelerator mass spectrometry (AMS) ^{14}C (see Table DR1 in the Data Repository[1]). Where such materials did not exist, sediments were collected and dated using optically stimulated luminescence (OSL; Table DR2). Analytical details of the dating methods are provided in the GSA Data Repository. The dates obtained are plotted against the stratigraphy in Figure 2.

A number of fluvial sand bodies >10 m thick were sampled, a thickness that is suggestive of sedimentation in a significant river channel. Thinner-bedded sediments are interpreted as overbank deposits. Our dates show that major channels existed prior to ca. 7.3 ka at Marot and ca. 5 ka at Tilwalla (Figs. 1 and 2). Fluvial sedimentation was active at Fort Abbas until after 5.7 ka, and at Tilwalla the youngest such sediments postdate 4.9 ka. OSL dating of the overlying dunes at Chak 102DB shows that these had started to accumulate after 4.5 ka but before 1.4 ka. Our new ages thus point to a number of fluvial channels on the edge of the Thar Desert that stopped delivering flow to Cholistan after 4.5 ka, but before 1.4 ka. The largest channels appear to date back to at least 49 ka (Fig. 2D), but were also active at 4.9–7.5 ka in the Marot and Tilwalla areas.

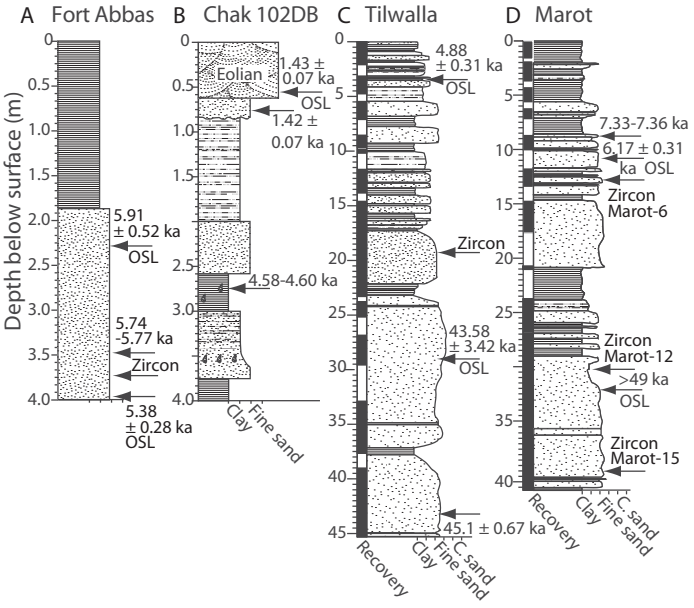

Figure 2. Sedimentary logs for each of the sections considered in this study showing the lithology, location of the optically stimulated luminescence (OSL) and ^{14}C accelerator mass spectrometry dates, and the position of the samples taken for zircon U-Pb dating. A and B: Trench sites. C and D: Drill cores. Thick sand bodies are interpreted as channel fills, while thin-bedded sediments are interpreted as overbank deposits. See Figure 1 for location.

ZIRCON DATING

We investigated the possible geometries of the river system through dating zircon sand grains using the U-Pb method (see the GSA Data Repository for analytical details). These ages represent the time at which the zircon crystals cooled below ~750 °C and are known to vary in different parts of the Himalaya, making them good provenance proxies (DeCelles et al., 2000) that have already been successfully applied to the Indus drainage (Clift et al., 2008). Grains dating at 0–300 Ma are associated with erosion from the Karakoram and Transhimalaya, those at 300–750 Ma are linked to erosion of the Tethyan Himalaya, 750–1250 Ma correlate with the Tethyan and Greater Himalaya, and 1500–2300 Ma are eroded dominantly from the Lesser Himalaya. Recently zircons from each of the major tributaries of the Indus were dated and different age populations were found, reflecting the diversity of the geology in the headwaters of each stream (Alizai et al., 2011a). This work makes the Indus one of the best-characterized rivers on Earth for looking at provenance evolution, and because each major river has been fingerprinted, its sediments may be identified in the floodplains.

Modern river samples were taken near the Himalayan front to avoid reworking from the desert or floodplains and are considered to be representative of the flux in each river. Because seasonal variations in sediment loads have been documented in the Nepalese Marsyandi River (Garzanti et al., 2007), sampling was consistently done during the dry season to minimize this influence. The extent of variation in zircon ages between the Indus tributaries is beyond the seasonal changes in the Marsyandi. To avoid grain size sorting affecting the results, data were obtained from grains within a narrow size range (>60–150 μm). Transport processes may affect the total concentration but not the range of zircon ages in any sample because zircon is a particularly robust phase. Earlier work has shown that zircons from the Indus delta can provide a representative image of erosion in the mountains despite much greater transport distances compared to this study (Clift et al., 2004). Ideally we would compare river sands of the same age as the floodplain sands because changing climatic conditions influence the loci of erosion and are known to vary the yield of zircons from different parts of the drainage on millennial time scales (Clift et al., 2008). Basins with little climatic variation (e.g., the Beas and Ghaggar) will be more stable than those spanning zones of variable precipitation such as the Sutlej where climate change can cause erosion maxima to migrate. Nonetheless, certain characteristics cannot be affected by climatic changes, such as the lack of zircons dating at 1500–2300 Ma in the Beas because there is almost no Lesser Himalayan rock exposed in this catchment (Alizai et al., 2011a). While temporal variations will change erosion, we do not expect the modern river zircon ages to be radically different from those shed from the Himalaya in the Pleistocene.

If the drainage pattern had remained approximately stable since the Pleistocene, then we might expect the sands recovered from the Cholistan region to resemble those rivers now closest to the sites. Figure 3 shows that the zircon age populations from Holocene sands from Marot, Fort Abbas, and Tilwalla have major differences with sands carried today by both the Sutlej and the Ghaggar that supposedly formed the headwaters of the paleo–river system in that area (Agrawal and Sood, 1982; Kar and Ghose, 1984). Sands from Tilwalla have a major population of 300–750 Ma zircons (39% of total), while this group is much less abundant in the Sutlej (10%), Ghaggar (17.6%), and Yamuna (5.7%). Instead, the Tilwalla sands more closely resemble the sands in the Beas River where 300–750 Ma zircons make up 61% of the load (Alizai et al., 2011a). Grains younger than 300 Ma in all the Holocene sediments are originally from the trunk Indus as no such sources exist to the east, so that these grains must be

[1]GSA Data Repository item 2012056, Table DR1 (^{14}C AMS ages for boreholes), Table DR2 (OSL ages), Table DR3 (U-Pb ages for detrital zircon grains), and Table DR4 (results of K-S tests for similarity between zircon populations), is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

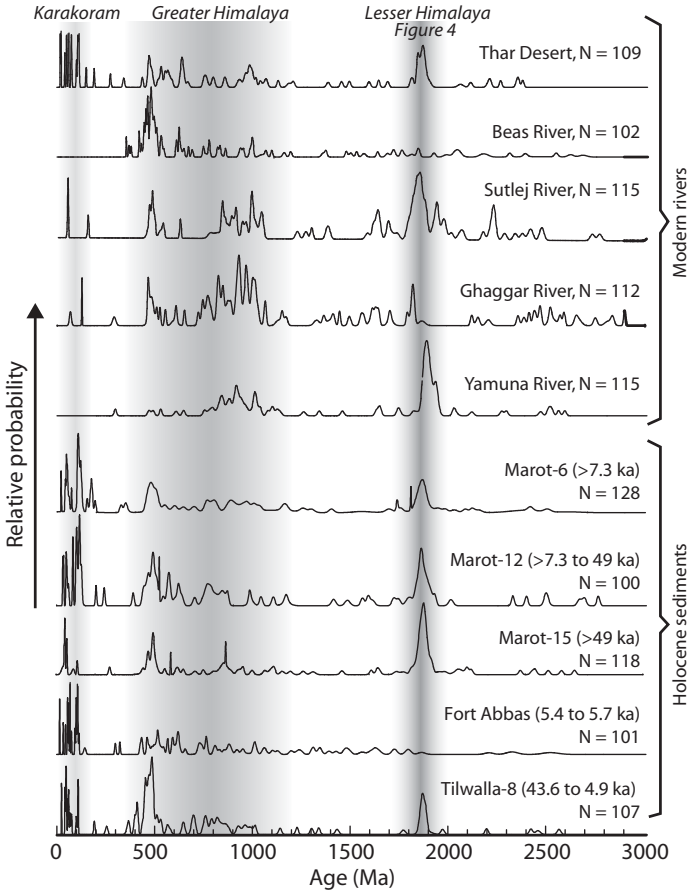

Figure 3. Probability density plots of U-Pb ages of zircon grains in sands from modern rivers, sand dunes, and the mid Holocene sediments sampled from the floodplain. Note the poor match between the sands at Marot, Fort Abbas, and Tilwalla compared to the Sutlej or Ghaggar.

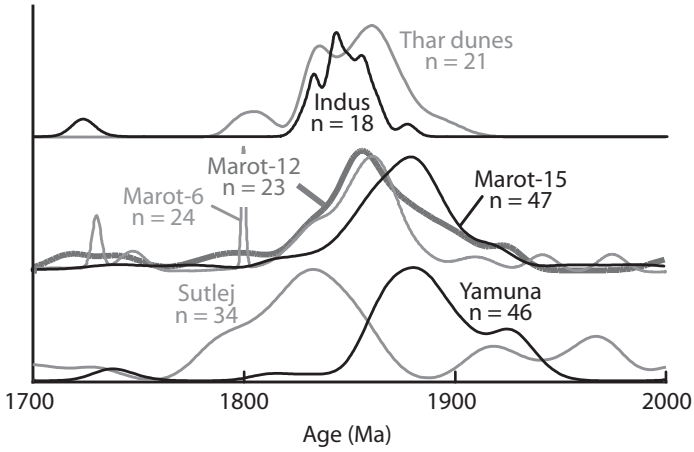

Figure 4. Probability density plots of U-Pb ages of zircon grains from the Marot borehole compared to possible source rivers. The peak at ca. 1800 Ma matches well with the Yamuna in Marot-15, but is more like the Sutlej or Thar dunes in Marot-12 and Marot-6.

reworked via dunes in the Thar Desert (Alizai et al., 2011a). We interpret the Tilwalla sand as being largely the product of sedimentation from a paleo–Beas River because we consider this solution to be more likely than a fourfold relative increase in erosion from the Tethyan Himalaya within the Sutlej under different climatic conditions. The Ghaggar River is too small to dominate a mixed flow with either the Beas or the Sutlej and cannot explain the provenance of the Tilwalla sand.

Dating of zircon grains from Marot reveals different proportions of age populations compared to Tilwalla. Specifically there are more (39%) grains dating 300–750 Ma, diagnostic of the Tethyan Himalaya, and fewer (18%) Lesser Himalayan (1500–2300 Ma) grains compared to the oldest sample, Marot-15, which has 17% and 52% of these two groups respectively. This difference could be explained by two separate channels in this region, although not necessarily both active at the same time. The Marot-15 sample (deposited >49 ka) contains zircons that are most similar to the Sutlej and Yamuna populations (Fig. 3). Kolmogorov-Smirnov (K-S) statistical tests show that this sand is not resolvably different from either river (Table DR4). However, considering only those grains dated at 1800–2000 Ma, the Yamuna zircons are statistically resolved as being older than those in the Sutlej, and are most similar to the Marot-15 sands (Fig. 4), favoring a link with the Yamuna, not the Sutlej at that time. No other modern river is known to have abundant grains centered around 1875 Ma, leading us to reject the possibility that a climatically disturbed Sutlej could explain the provenance signal.

We further reject the possibility that the Marot-15 sands are all reworked locally from the desert, as this would result in a mixed population. Although it is possible that seasonal variations are responsible for the apparent differences between the modern Sutlej and Yamuna, we consider this unlikely given that sampling was all done in the dry season, that there is a significant number of grains dating at 1800–2000 Ma in each sample, and that K-S testing demonstrates the separation of the populations measured. It seems unlikely that so few ca. 1875 Ma grains would be present in the Sutlej when they were found commonly in the Yamuna if this difference was not real. Furthermore, we note that sample Marot-12, dated between 7.3 and >49 ka, has an 1800–2000 Ma population more similar to the Sutlej and is resolvably different from both the Yamuna and Marot-15. The younger Marot-6 sand (deposited ca. 6–7 ka) shows a quite different assemblage with fewer 1800–2000 Ma grains and more grains younger than 300 Ma. These zircons test as being most similar to those from the desert dune sands. We interpret this transition to represent weakening of river flow prior to its eventual abandonment, much as inferred from Pb isotopic work from the sands at Tilwalla (Alizai et al., 2011b).

The sample from Fort Abbas (Fig. 3) is particularly enigmatic, not least because of its apparent position along the main stream of the Ghaggar-Hakra. The lack of an 1800–2000 Ma population argues against a connection to the Yamuna or Sutlej at 5.7 ka, but similarly it is hard to sustain a simple link to the measured Thar Desert sample. One sand sample is unlikely to fully describe the diversity in any of these reservoirs, but the very high number of grains younger than 300 Ma makes a dominant source from the Thar Desert hard to avoid.

CONCLUSIONS

Our provenance studies now allow some important constraints to be placed on reconstruction of the river systems since the mid Holocene. Our data show that the Yamuna likely flowed west, not east as it does now, at least prior to 49 ka. Such a change in drainage pattern is possible because the Yamuna reaches the Himalayan foreland close to the crest of the drainage divide. Why the switch from Indus to Ganges occurred is unknown but could reflect a number of processes diverting the river east, such as an avulsion event driven by autocyclic processes, as seen for example by the 120 km shift of the Kosi River in 2008. The Beas River was delivering material directly to Tilwalla prior to 10 ka, which in turn would require the Sutlej to have flowed into the Ghaggar-Hakra east of Marot. This means the northern Thar region must have been an

area with several major confluences and a large river with a combined flow arguably sufficient to reach as far as the Arabian Sea (Fig. 1). While drainage from the Yamuna may have been lost from the Ghaggar-Hakra well before development of the Harappan Civilization, flow from the Beas and Sutlej may have been more recent in Cholistan, if still prior to 10 ka. Loss of these rivers might be expected to have had a catastrophic effect on sustaining settlement in this region, but our evidence argues against this. Water in the small Ghaggar-Hakra (or Sarasvati) River would have been further reduced by monsoon weakening from 4.2 ka (Enzel et al., 1999; Staubwasser et al., 2003; Wünnemann et al., 2010), but evidence for dramatic changes in water sources was much earlier. While drainage capture is dramatic in the eastern Indus Basin in the late Quaternary, it appears to have occurred prior to human settlement and not to have directly caused the Harappan collapse.

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